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Notes on solar radiation and natural illumination

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1. Solar Radiation

1.1. In Fig 1 some properties of the solar spectrum are illustrated.

Three broad bands can be recognised viz

ultra-violet (U-V) - with a wavelength less than about 0.4μ ($1\mu = 10^{-4}$cm)

visible - lying between 0.4μ and 0.7μ

infra-red - extending from 0.7μ to 3.0μ or more.

Most of the U-V is filtered out in the high atmosphere; and at ground level, about 44% of the total energy reaching the surface is in the "visible" bands; the remaining 56% being almost entirely in the infra-red.

1.2. Fig 2 indicates the general character of total radiant income on unit area (usually one square centimetre) of horizontal surface in the course of a day.

The area of the curve corresponds to the total input of energy; the height of the curve - as at PQ - corresponds to the intensity (energy per unit time) arriving in some small interval of time Δt.

The units used for solar radiation measurements are:

(for total energy) - gram cals per cm^2 (or "langley") or milliwatt-hours per cm^2

(for intensity) - gram cals per cm^2 per minute or milliwatts per cm^2

The conversion factors are:-

for total energy: 1 gr cal per cm^2 = 1.16 mW hrs per cm^2

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for intensity: 1 gr cal per cm^2 per min = 69.8 mW per cm^2

(Derivations of these and other conversion factors are set out in Appendix I).

2. Natural Illumination

Illumination relates to the response of the human eye to radiation within certain wave bands. For our present purposes we can consider the intensity of illumination of any surface as arising from the actual flux of luminous energy falling upon it compared with that which would occur using an arbitrary but agreed standard source.

The luminous energy emitted by a source is measured in lumens and that falling upon unit area of a surface in unit time is measured in foot-candles or lux (metre-candles).

In Fig 3 imagine two concentric spheres with a centre at P. Suppose the smaller sphere is of radius 1 ft, and the larger 1 metre and furthermore that luminous energy is radiating outwards from P within a unit solid angle, and that the boundaries of the angle cuts the smaller sphere at ABCD and the larger at abcd.

The areas of ABCD and abcd will be respectively 1 sq ft and 1 sq metre, and one lumen emitted at P will give an illumination of one foot-candle on ABCD and one metre-candle on abcd, and since

$$\frac{\text{area ABCD}}{\text{area abcd}} = \frac{1^2}{(3.281)^2} = \frac{1}{10.76}$$

then:

1 ft-candle = 10.76 metre-candles or lux

3. Relationship of luminous energy and illumination with total solar radiation

3.1. In Fig 4 suppose the small shaded area to coincide with a sq cm of horizontal ground surface. If the illumination of abcd is of the intensity of one lux (due to the emission of one lumen of energy from P) then the amount of luminous energy reaching the small area is 10^{-4} lumens. In the open, this would be associated with an input of solar energy expressed in terms of gr-cals per cm^2 per min or in terms of milliwatts per cm^2.

The conversion from one system to the other is through the concept of the "luminous efficiency of daylight" (LE) although one authority (Moon 1963)

prefers the term "luminous efficacy." . Some estimates are

(after Atkins & Poole)	Bright, direct sunshine	90.8 lumens per watt
	" sky light	125.7 "
	Sun plus sky on clear days	107.8
(from Kimball)	Sunny days	103.4
	Cloudy days	108.1
	diffuse sunlight	125.8
(Blackwell)	cloudless day, about noon March. Kew	122.0

It is well established that the L.E. of diffuse radiation from sky and cloud is greater than that of the solar beam. A "whole sky" value of 108 lumens/watt appears to be a little low. Possibly a figure of 110 lumens/watt may be taken as a general average for all conditions.

Using this value of LE we find (App I( )):-

one gr cal per cm^2 per minute = 76,560 lux

or 7115 ft candles

(and proportionally for other LE e.g. LE = 125 lumens per watt gives 87,200 lux or 8110 ft candles).

3.2. The integrated values over time (e.g. daily totals) require the following conversions (see App I for details).

one gr cal per cm^2 = 11.6 x L.E. lux-hours

= 1.276 kilo-lux hours (for LE = 110 lumens/watt)

For LE = 122 the multiplying factor becomes 1.41.

Also one mW hr/cm^2 = (LE) x 10^{-2} kilolux hours.

E.g. Daily total of 500 gr cals per cm^{-2} and LE = 110 lumens/watt

Gives $500 \times 1.16 \times 10^{-3} \times 110$ lumen hours

$= 500 \times 1.16 \times 10^{-3} \times 110 \times 10^{4}$ lux hours

= 638 Kilolux hours

= 59300 ft-candle hours

4. Cautionary Note

The luminous efficiency (LE) quoted above is for unfiltered solar radiation. Under glass, LE may assume different values: in growth cabinets, using artificial sources of light, LE will be very different.

Appendix I

(a) Intensity of solar radiation

One gram cal is equivalent to 4.1855 joules = 4.1855×10^7 ergs of energy.

1 watt = one joule per sec or 10^7 ergs per sec (i.e. a watt represents a rate of delivery of energy of 10^7 ergs each second).

1 gr cal per min per cm^2 = 4.1855×10^7 ergs per min per cm^2

$$= \frac{4.1855 \times 10^7}{60} \text{ ergs per sec per } cm^2$$

$$= 69.8 \times 10^4 \text{ ergs per sec per } cm^2$$

$$= 69.8 \text{ mW per } cm^2$$

(Since 1 watt = 10^7 ergs/sec and 10^4 ergs = 1 mw)

(b) Total amount of solar radiation

One gram cal = 4.1855×10^7 ergs

One mW = 10^4 ergs per sec

Thus it will take $\frac{4.1855 \times 10^7}{10^4}$ seconds to deliver 4.1855×10^7 ergs at the rate of 1 mW

$\therefore$ Time = 4.1855×10^3 seconds

= 1.16 hours

Thus a total input of 1 gr cal per cm^2 of surface can be obtained from a rate of 1 mW lasting for 1.16 hours.

1 gr cal per cm^2 = 1.16 mW hrs per cm^2

(c) Illumination/radiation conversions

(i) Intensities

One gr cal per cm^2 per min = 69.8 mW per cm^2

= .0698 watts per cm^2

.0698 x LE (≈110) lumens per cm^2

= 7.656 "

But 1 lumen/sec from P impinging on a square metre gives an illumination of 1 lux

$\therefore$ 7.656 lumens arriving at one sq cm must imply an illumination level

at the surface of $7.656 \times (10^2)^2$ = 76,560 lux

= 7115 ft candles

Kimball (Smithsonian Tables) suggests:

clear sunny days: 6700 ft candles

cloudy days: 7000 "

(ii) Time integrals

1 gr cal per cm^2 = 1×1.16 mW hrs per cm^2

= 1.16×10^{-3} watt-hours per cm^2

= 1.16×10^{-3} x LE lumen hours per cm^2

This corresponds to an **input** over 1 m^2 of

= $1.16 \times 10^{-3} \times LE \times (10^2)^2$

= $1.16 \times 10 \times LE$

(Assuming LE = 110 lumens/watt) = 1.276×10^3 lux-hours

= 1.276 Kilo lux-hours

Thus a daily value of 500 gr cals per cm^2

= 638 kilo lux hours.

Using LE = 122 the multiplying factor becomes 1.41. This agrees with Black (1960).

$$\left[\begin{array}{l}\text{Mean monthly illumination} \\ \text{kilo-lux hours per } \underline{\text{day}}\end{array}\right] = 1.405 \left[\begin{array}{l}\text{Mean monthly global} \\ \text{radiation in gr cals per} \\ cm^2 \text{ per day}\end{array}\right] \qquad -15.2$$

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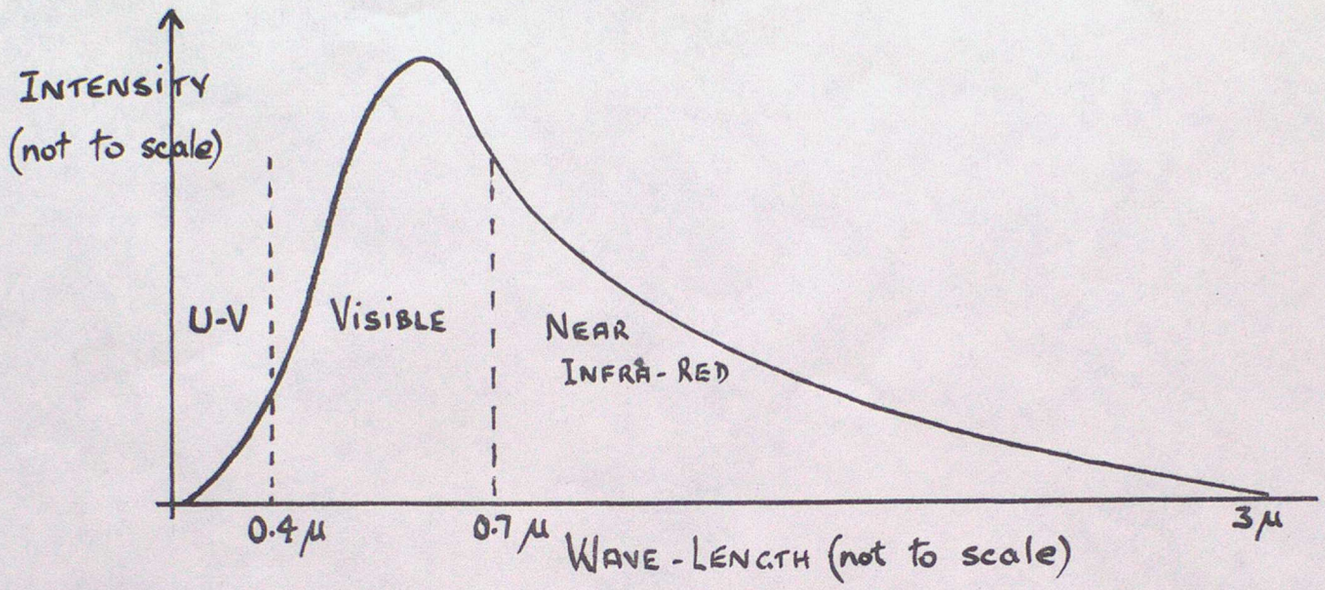

Fig 1 SCHEMATIC DIAGRAM SHOWING ENERGY DISTRIBUTION IN THE SOLAR SPECTRUM.

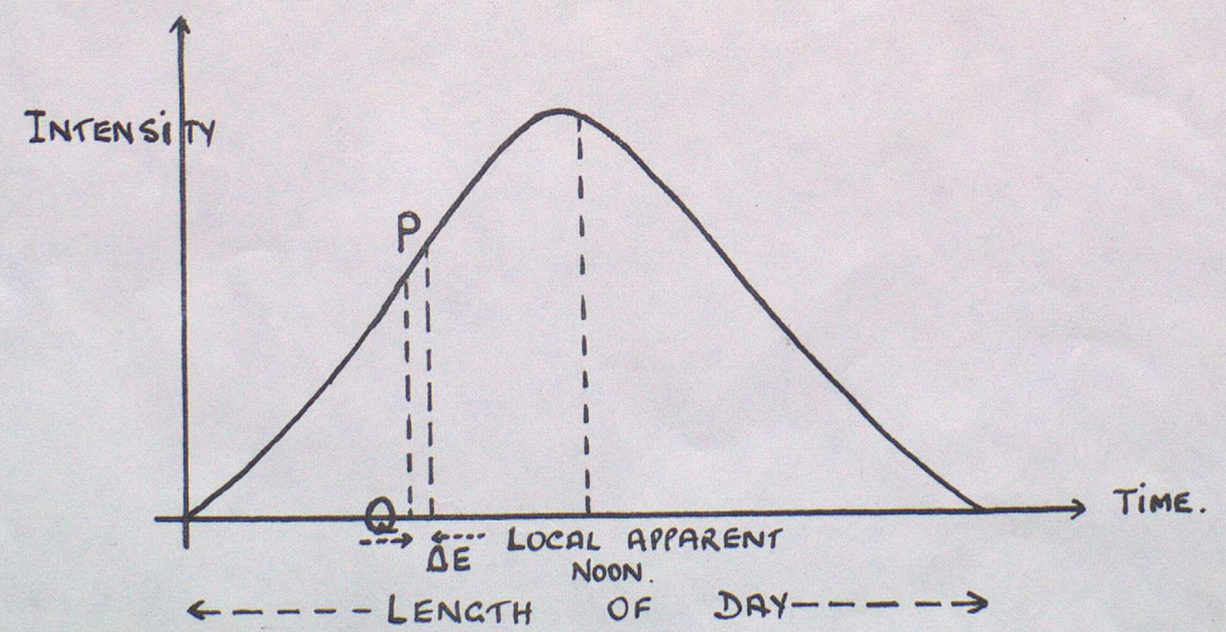

Fig 2 SCHEMATIC DIAGRAM TO ILLUSTRATE DIURNAL VARIATION OF TOTAL SOLAR RADIATION ON A HORIZONTAL SURFACE.

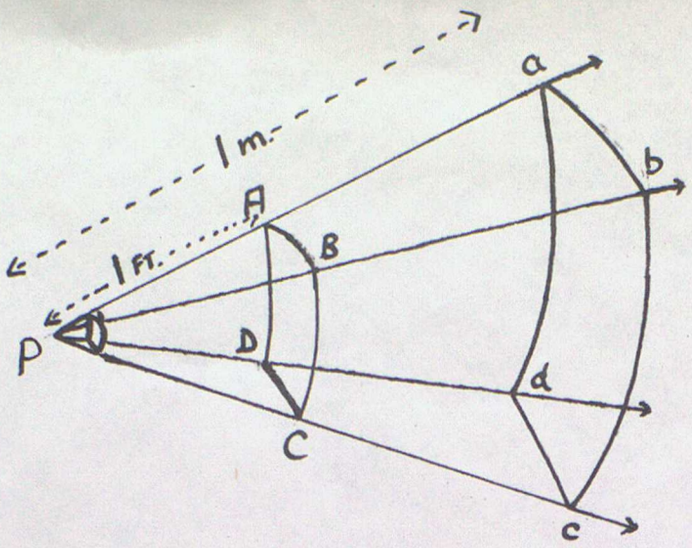

Fig 3 SCHEMATIC DIAGRAM TO SHOW RELATIONSHIP OF ILLUMINATION BY UNIT SOURCE ON PORTIONS OF SPHERES OF DIFFERENT RADII.

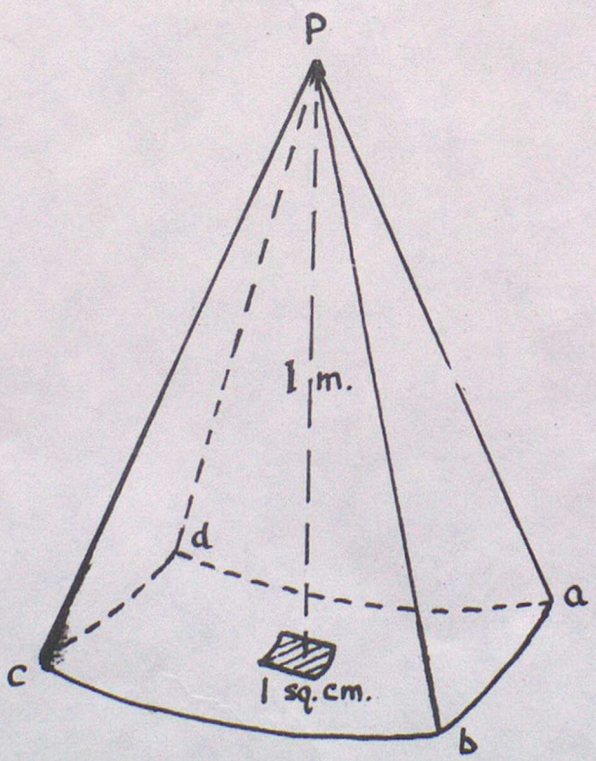

Fig 4 TO ILLUSTRATE ILLUMINATION OF 1 SQ. CM. OF HORIZONTAL SURFACE BY UNIT SOURCE AT 1 METRE DISTANCE.